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A.A.M. Delil, A. Pauw, A.A. Woering and B. Verlaat*

* National Institute for Nuclear and High-Energy Physics, The Netherlands

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AMS-2 TRACKER THERMAL CONTROL SYSTEM: DESIGN AND THERMAL MODELLING OF THE MECHANICALLY PUMPED TWO-PHASE CO_2 LOOP

A.A.M. Delil, A. Pauw, A.A. Woering
National Aerospace Laboratory NLR, P.O. Box 153, 8300AD Emmeloord, The Netherlands
(Phone +31 527 8444, Fax +31 527 8210, adelil@nlr.nl)

and

B. Verlaat
National Institute for Nuclear Physics and High Energy Physics NIKHEF, Amsterdam, Netherlands

ABSTRACT

The AMS-2 TTCS is an ISS-related two-phase heat transport technology development at NLR and NIKHEF. The TTCS, Tracker Thermal Control System, concerns the development of a mechanically pumped two-phase carbon dioxide cooling loop for the Tracker, the most critical part of the Alpha Magnetic Spectrometer AMS, an International Space Station attached international payload searching for anti-matter, dark matter and lost matter. AMS-2 is an improved AMS-1, the demonstration experiment that has successfully flown on STS-91. AMS-2 is manifested on Shuttle flight UF-4 for a mission of three to five years on ISS. The paper discusses the TTCS objectives and requirements, the trade-off based choice and experimental feasibility demonstration of the mechanically pumped two-phase CO2 cooling loop, the development of test set-ups, including and a full-scale TTCS simulation loop and its components. Results of experiments and of thermal modelling and simulations will be discussed in detail.

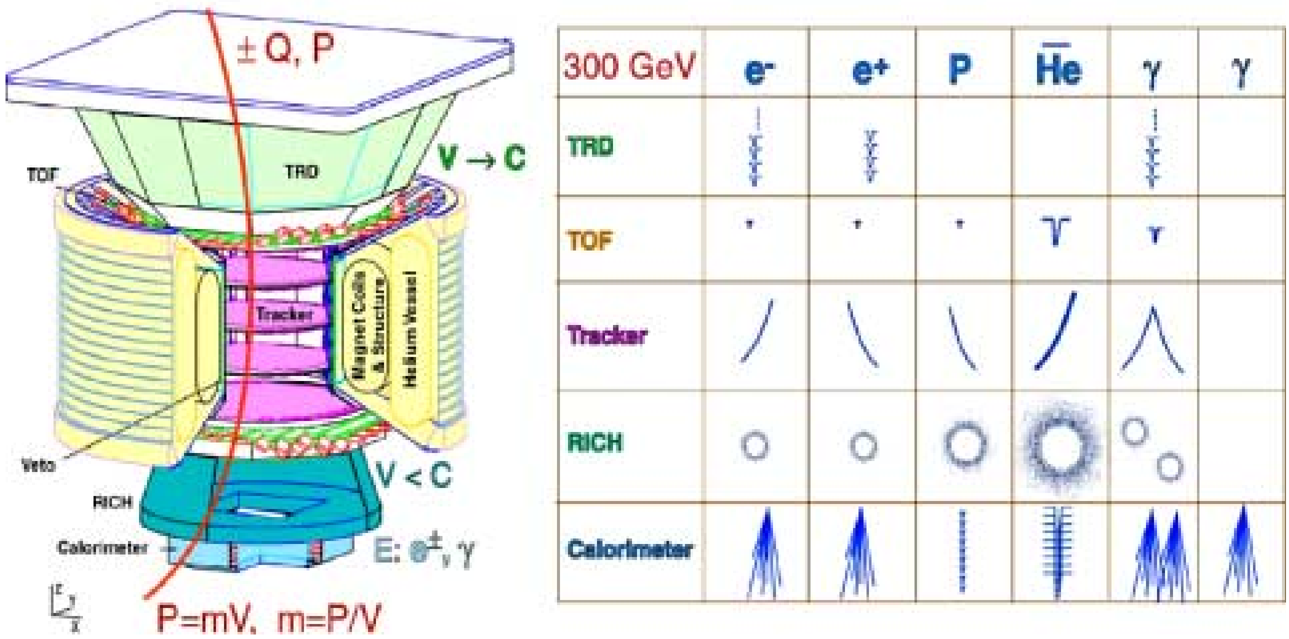


Figure 1. Alpha Magnetic Spectrometer AMS schematic and the particles to be detected by signals of different detectors (electrons, positrons, protons, Helium nuclei and gamma rays).

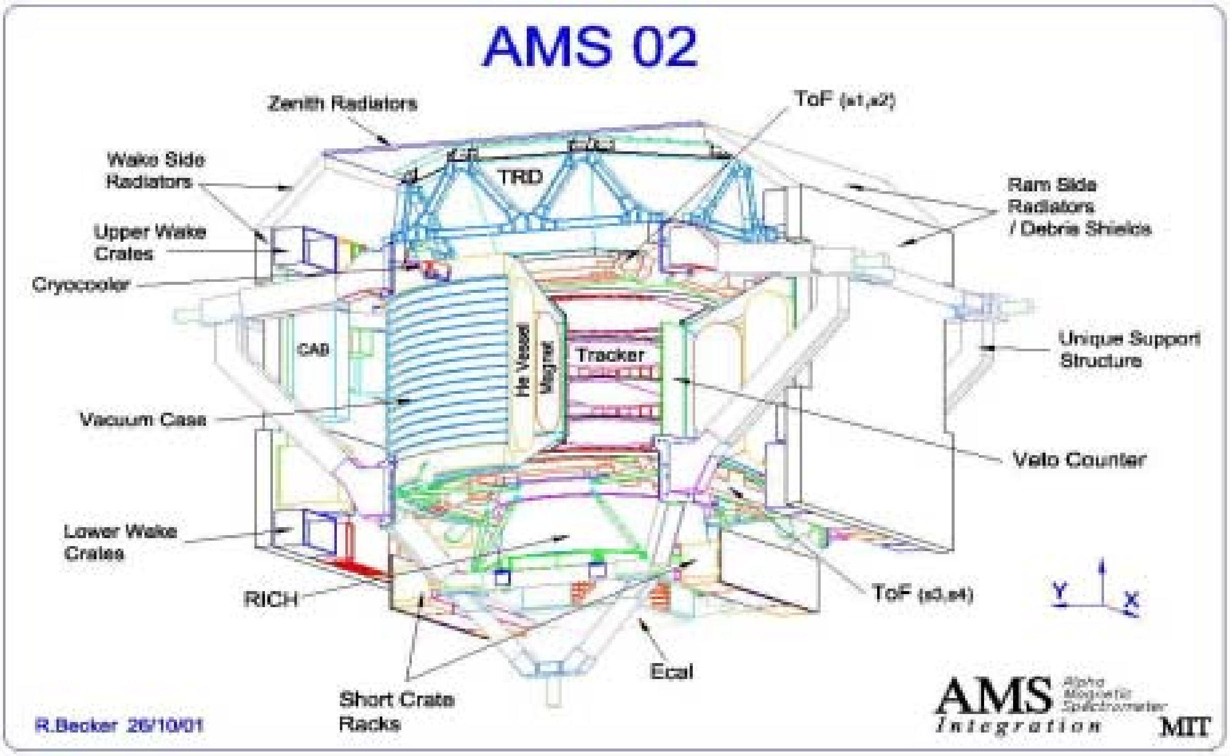


Figure 2. Picture of the Alpha Magnetic Spectrometer AMS-2.

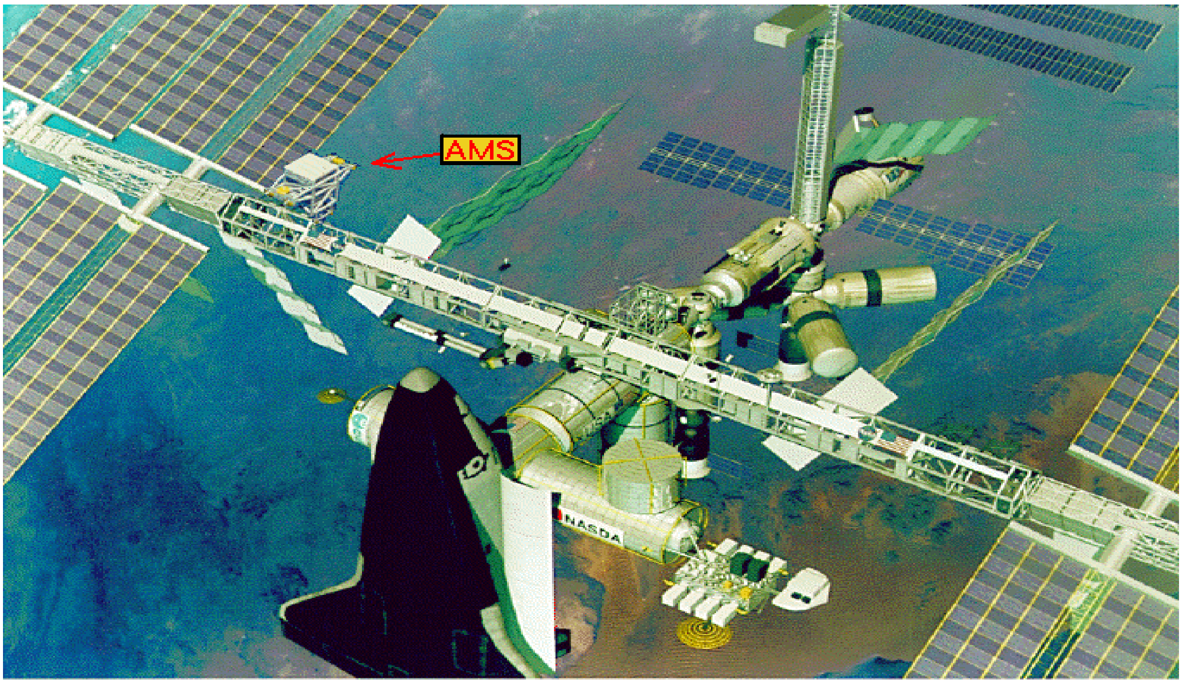


Figure 3. AMS-2 location on ISS.

BACKGROUND

The Alpha Magnetic Spectrometer AMS[1] is an international experiment, led by Nobel Prize laureate Samuel Ting (MIT), searching for anti-matter, dark matter and lost matter. It is a particle detector for high-energy cosmic rays (Figs. 1, 2), consisting the sub-detectors: The (Silicon) Tracker, the Time of Flight (ToF) system, the Veto Counters, the Transition Radiation Detector (TRD), the Synchrotron Radiation Detector (SRD), the Ring Imaging Cherenkov Counter (RICH), the Anti-Coincidence Counter, and the Electromagnetic Calorimeter. The demonstration experiment AMS-1 has successfully flown in June 1998 on the Space Shuttle Discovery (STS-91).

AMS-2, an improved (resolution) version of AMS-1, is manifested on Shuttle flight UF-4.1 (scheduled for launch mid October 2005) for a 3 to 5 years mission as attached payload on the International Space Station ISS (Fig. 3).

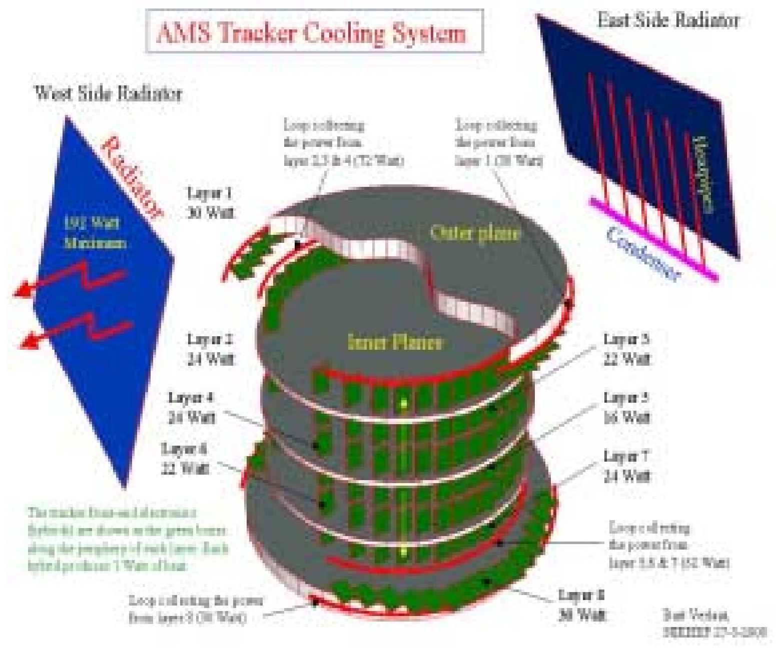
The thermal issues of AMS-2 are far more demanding/critical than in AMS-1, as of the replacement of the heavy (high thermal capacitance) magnet by a liquid Helium II cooled super-conductive one, and by the long mission duration. Therefore a team consisting of NLR, NIKHEF, Geneva University and IFN Perugia is developing a cooling system for the most critical part, the so-called Tracker Thermal Control System TTCS.

The TTCS contract offers NLR the possibility to use two-phase thermal control expertise obtained in the past for the challenging task to develop and operate an advanced, demanding system like the TTCS, probably being the first full- size mechanically pumped two-phase thermal control system in space. NLR joined the AMS collaboration as this offers also the possibility to scientifically exercise with the two-phase cooling loop during the various dormant periods in the AMS experimentation.

The to be gathered information is expected to yield a far better understanding of the physics of two-phase flow and heat transfer in micro-gravity, which is essential for developing future two-phase thermal control systems for spacecraft applications.

HYBRID CO_2 MPL IS TTCS BASELINE

The Tracker, located inside the vacuum case (Figs. 1, 2), is surrounded by the cryogenic magnet, which is not allowed to receive any heat from inside. Moreover the Tracker has severe requirements with respect to spatial and temporal temperature requirements (Fig. 4). This and the existing complicated 3-D configuration, requires that the power dissipated in the Tracker, 192 W, has to be removed to two thermally out of phase radiators (one in RAM, one in Wake direction) to be dumped into space (Fig. 4). This could be done by a mechanically pumped two-phase loop system, by a mechanically pumped liquid loop and by a capillary pumped loop system. The latter system requires heat collecting heat pipes to transport the dissipations from the silicon front-end electronics to the capillary system, as a capillary system can't properly handle evaporators (heat sources) in series. In addition, a parallel capillary system[2, 3] leads to unacceptable tubing length and mass, which can't be accommodated by the existing 3-D Tracker configuration. Finally it is remarked that the chosen system has to be installed two-fold to guarantee the full redundancy required.



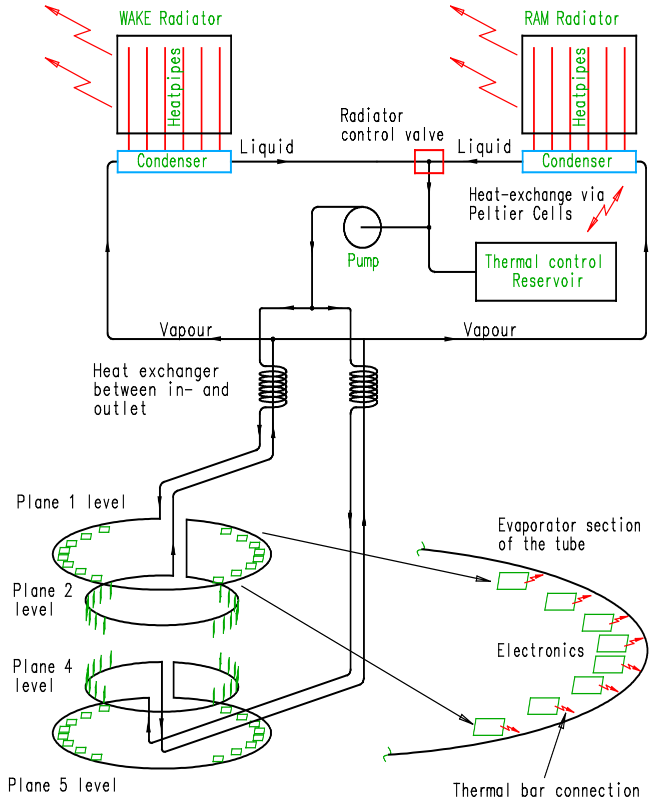
Silicon wafer requirements:

- **Operating temperature:** **-10 ºC / +25 ºC**
- **Survival temperature:** **-20 ºC / +40 ºC**
- **Temperature stability:** **3 ºC per orbit**
- **Maximum accepted gradient between any silicon:** **10.0 ºC**
- **Dissipated heat:** **2.0 W EOL**

Hybrid circuit requirements:

- **Operating temperature:** **-10 ºC / +40 ºC**
- **Survival temperature:** **-20 ºC / +60 ºC**
- **Dissipated heat:** **192 W, 1 W per hybrid pair**

Figure 4. Silicon Tracker thermal issues.



- **Maximum expected operating pressure: TBD (depends on maximum TTCS temperature):**
  125 bar @60°C, 140 bar @70°C,
  160 bar @80°C, 175 bar @90°C
- **Pressurized volume ca. 3 liter CO_2 per loop:**
  600 cc tubes, 2.5 liter accumulator
- **2 Identical completely separated loops (1 for redundancy)**
- **2 serial evaporators in parallel per loop**
- **2 parallel condensers controlled per loop controlled by a 3-way valve**
- **Pressure control by thermal control reservoir**
- **Thermal control using the USCM**
- **Critical parts in redundant configuration (pump, valves)**
- **Most fluid components in 2 dedicated TTCS boxes on the USS at wake side**
- **RAM and WAKE heat pipe radiator**
- **All hardware in debris safe areas, where a debris shield is added if needed**

Figure 5. Hybrid MPL concept for TTCS.

Keeping the above in mind and following in the next the references contents [3, 4], it can be said that:
- A series or hybrid two-phase Mechanically Pumped Loop (MPL) is well compatible with existing Tracker hardware. It is characterised by minimal material inside or near the tracker field of view. It is directly connected to the thermal bars. Consequently no additional heat collector will be needed.
- Multiple-source heat input is possible, with minimum T-gradients (< 1 K). It has also the possibility to implement a fully redundant system. Costs and mass are relatively low. The only drawback is the mechanical pump.
- A Single-Phase (liquid) Mechanically Pumped Loop (SPL) has more or less the same layout as the MPL option, so it is relatively easy to fall back on the SPL solution, in case of unforeseen (serious) problems with the MPL development. It has the possibility of parallel and counter-current flow system set-up. It is a low-risk design, as there is sufficient experience in space with SPL's. Main drawbacks are the far larger temperature gradients (say 10 K), as compared to the nearly isothermal MPL, and larger dimensions.
- Any parallel two-phase system (MPL, LHP, CPL) can not to accommodate the existing Tracker hardware multiple location heat input, by it self in one stage, as of the huge mass and (not available) space needed, induced by redundancy. A two-stage approach needs an additional heat collector is needed: Heat pipe or TPG-flange, leading to. significant mass increase and serious integration problems.

The above makes obvious that by far the best solution is the series or hybrid two-phase MPL. A parallel or hybrid SPL is a possible back-up solution, but at the cost of more massy and lengthy lines and larger pumps. Parallel concepts are non-recommendable or impossible solutions.

CO_2 has to be the working fluid since:
- It is considered to replace Freon-like refrigerants, as it is environment friendly and non-toxic. It is used for nuclear power plant cooling, as it is inert for radioactive radiation. For AMS-2 this means no ISS safety-related problems.
- It has a very low liquid/vapour density ratio, Order (1-10), being profitable for a series 2-phase system; its alternative, ammonia: Order (10^2-10^3).
- CO_2 experience was gained at NIKHEF, where tests have proven the concept feasibility of CO_2 cooling for the LHCb Vertex detector [5]. For the Tracker this means small tube dimensions (3 mm OD) in case of 2 loops, low temperature drops (< 1 K) and low pumping power (< 10 W).

In addition it is remarked that[4]:
- The basic difference between mechanically pumped single-phase (caloric heat transport by the liquid) and two-phase systems (transport by latent heat of evaporation/ condensation). This implies for dissipating stations in series in

a single-phase system a temperature increase in the downstream direction of the loop. For two-phase systems, with evaporators in series, it means an increase of the vapour quality in the downstream direction, accompanied by a (usually small) decrease of the saturation temperature.

- In mechanically pumped two-phase loops, the flow pattern dependent heat transfer coefficient for convective flow boiling is reported [6] to be between say 4 and 5 kW/m^{2}K. This is not true for refrigerants (to be used in the TTCS) at qualities below 0.15 for which the value can increase to say 20 kW/m^2.K at qualities of less than 0.03 [6, 7]. Data from experiments with CO_2 in small diameter tubes confirm it[8]. The above implies that a mechanically pumped system has to be designed such that any evaporator exit quality is below 0.15 (preferably even much lower) for efficiency reasons.
- In the case of very lengthy mechanically pumped two-phase loop lines, the pressure (saturated temperature) gradient has to be kept small to guarantee a small end-to-end pressure (saturated temperature) difference. This is to meet the requested isothermality, and to keep the evaporator exit vapour quality below 0.15, as in flowing refrigerants the vapour quality usually increases with pressure decay (if one assumes isentropic flow[9]). Ethane is an exception: Quality increase below say 0.7, decrease above. Real flow is isenthalpic[10], meaning that the quality always increases, also for ethane.
- In conclusion: A dedicated hybrid two-phase CO_2 loop configuration, as it is schematically depicted in figure 3, will guarantee both the required isothermality and the preferred quality range.

TTCS CONCEPT

The proposed TTCS is the closed two-phase system (Fig. 5). The heat is absorbed in the evaporators and rejected space by the radiator panels at the condensers. As the mechanical pump provides the liquid flow rate needed, it has to be located after the condensers, as it needs pure liquid to operate properly. Consequently the condensers/radiators need not only to condense all vapour, but also to provide a certain amount of sub-cooling. The blue boxes on top are heat exchangers, thermally connect inlet and outlet of the evaporator (Fig. 6). In this way the absorbed heat can be used to heat the entering sub-cooled liquid from the pump so it gets close to the evaporative temperature needed in the Tracker. The evaporators consist of two parallel tubes each having an ID of 2.6 mm and a length of 10 m. These two tubes are serially cooling the hybrid circuits, located on the outer periphery of the Tracker. The parallel evaporator branches are routed as two rings following the widely distributed Tracker hybrids. The second branch is located similarly at the bottom of the Tracker. The evaporator tube is mounted with a copper connection bridge to the hybrid thermal support structure named thermal bars.

The figures 7 to 10 show details of the evaporators. Figure 7 depicts the thermal connection from the inner thermal bars to evaporator. Clearly visible is the bent configuration of the evaporator tube; which is needed to follow the stepped orientation of the tracker hybrid boxes. This stepped orientation is one of the reasons that a small diameter evaporator tube was selected as the baseline, because it seemed to be the only design that was compatible with the already existing tracker hardware. There are two tubes, one acts as the redundant line in the case of a failure. AMS-2 radiator panels are outside the experiment. They are covered with high emissivity and low solar absorptivity coatings/paints. The two opposite radiator panels are thermally speaking out of phase, meaning that there is always one radiator shaded from the sun, hence able to radiate waste heat to space. The evaporation temperature is adjusted by the system pressure. This pressure is controlled via the accumulator, a small reservoir with a mixture of vapour and liquid. A Peltier element controls the reservoir temperature, hence the system pressure by condenser flooding. The majority of the TTCS hardware is in a box outside on the support structure. The evaporators, heat exchangers and condensers are outside this box.

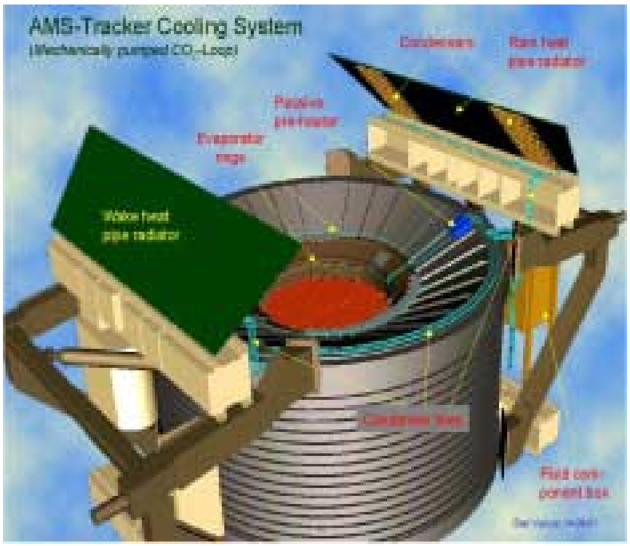
TEST SET-UPS AND TEST RESULTS

An open loop test set-up[4], built at NIKHEF to prove the feasibility of the TTCS evaporator concept for CO_2, consisted of an evaporator section connected to a liquid CO_2 filled bottle. The CO_2 flow was adjusted by a needle valve, the pressure in the test tube by a spring-relieve valve (at the exit). In the real TTCS all thermal bridges are individually connected to the to evaporator tubes. In the feasibility test set-up heat is applied over the test section tube wall using the electric resistance of the tube as heater. Flow, pressure drop and temperatures along the tube were measured. Figure 11 shows a picture of the test set-up and some test results, which suggest that CO_2 is an adequate refrigerant for the TTCS.Experiments were done next at NIKHEF[4] to confirm this in a closed loop test set-up (Fig. 12), which more realistically simulates the TTCS. Goals of the experiments were:

- To measure pressure drop characteristics and heat transfer coefficients at different flow rates, heat input and evaporation temperatures, for a 10 m long, 2.5 mm ID test evaporator, with helical sections between the long sections to correctly simulate the multiple bends in the real Tracker.
- To compare the test outcomes to theoretical predictions and experimental data produced in a NIKHEF/SINTEF CO_2 test set-up.
- To prove the merits inserting a heat exchanger (as pre-heater) between evaporator in- and outlet.
- To yield recommendations for further TTCS development, on pumping rates and evaporators.

Though many experiments have been executed[11], the results shown in the following figures pertain only to the 10 metres long, 2.5 mm ID evaporator performance, i.e.:

- Figure 13 showing the pressure and temperature drops, as a function of the mass flow, at 273 K.
- Figure 14 showing the heat transfer coefficients (HTC) and observed flow patterns versus vapour quality and heat flux, at 278 K and nominal flow 2.7 g/s.



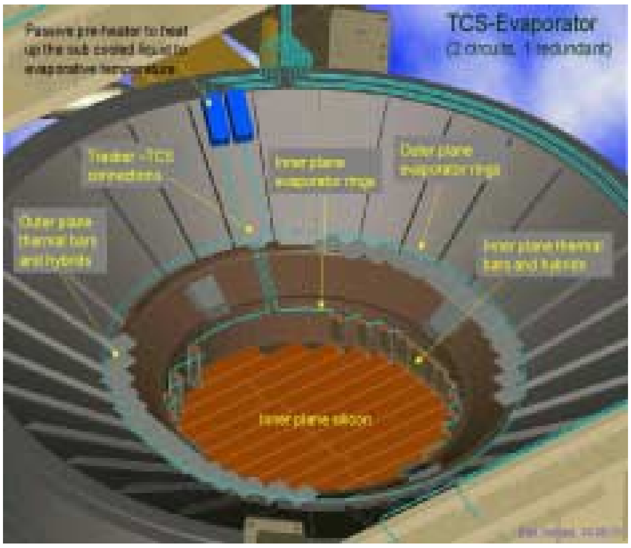


Figure 6. Artist's impression of the integrated TTCS and TTCS evaporator.

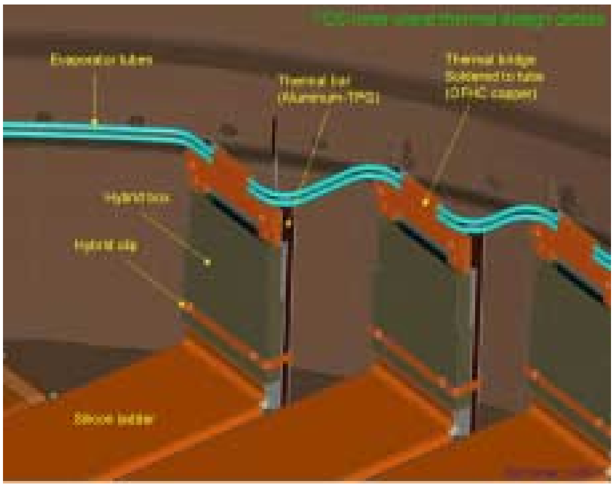


Figure 7. Evaporator connected to inner thermal bars.

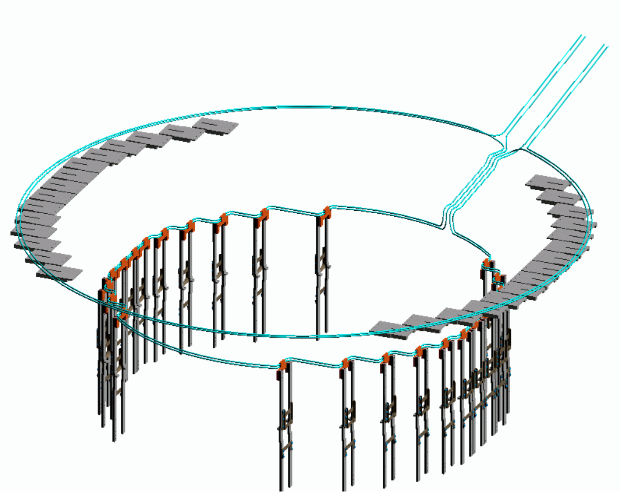


Figure 8. Complete thermal system inside the Tracker.

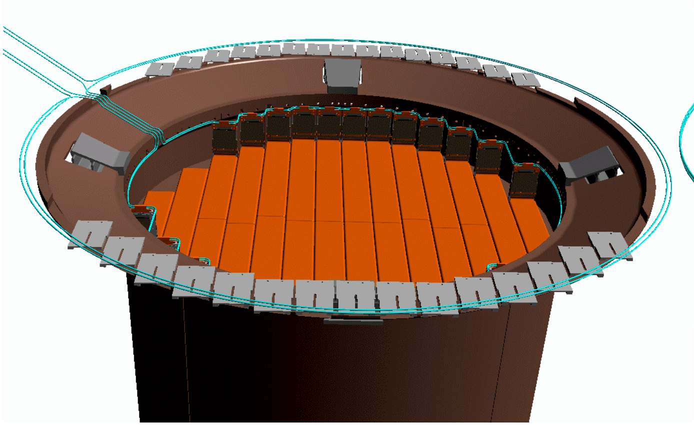


Figure 9. Complete overview of an evaporator in the Tracker.

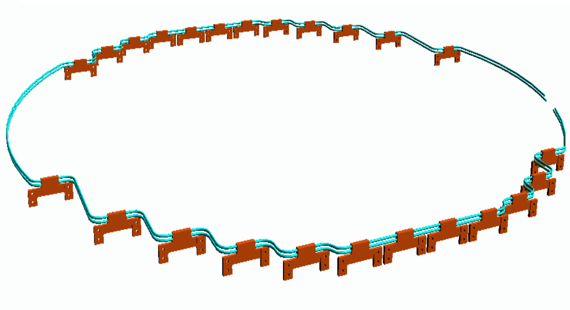
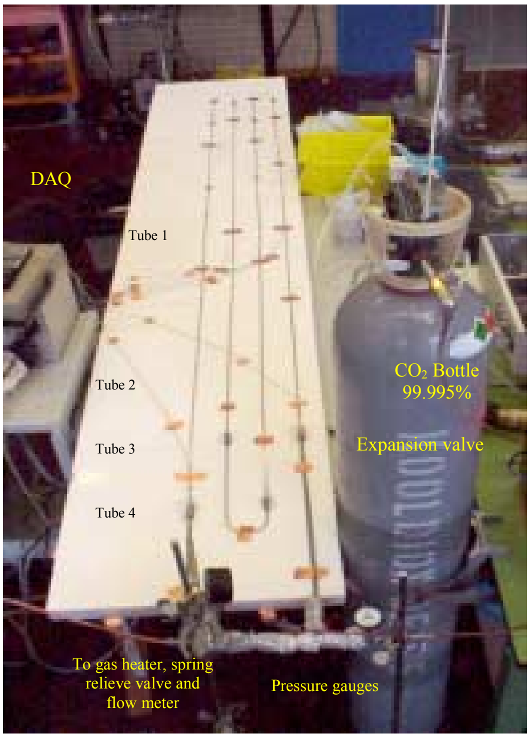
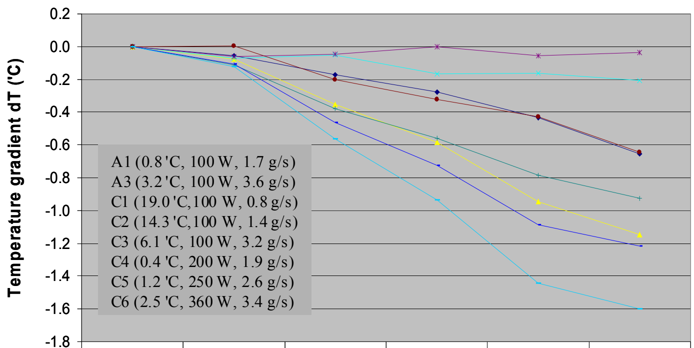


Figure 10. Inner planes evaporator.





	dT inlet (0m)	dT tube 1 (1m)	dT tube 2 (3.4m)	dT tube 3 (5.8m)	dT tube 4 (8.3m)	dT outlet (9.3m)
A1	0.0	-0.1	-0.2	-0.3	-0.4	-0.7
A3	0.0	-0.1	-0.4	-0.6	-0.9	-1.1
C1	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
C2	0.0	-0.1	0.0	0.0	-0.1	0.0
C3	0.0	0.0	-0.2	-0.3	-0.4	-0.6
C4	0.0	-0.1	-0.4	-0.6	-0.8	-0.9
C5	0.0	-0.1	-0.5	-0.7	-1.1	-1.2
C6	0.0	-0.1	-0.6	-0.9	-1.4	-1.6

Figure 11. Feasibility demonstration: test set-up and test results.

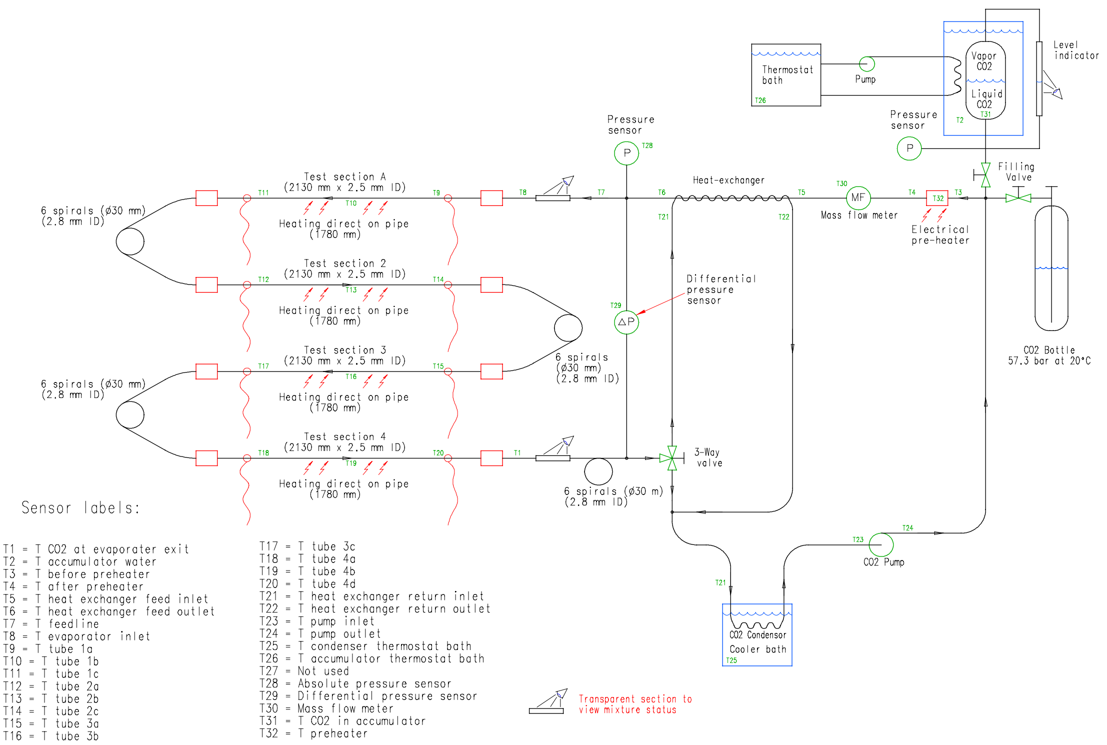


Figure 12. Schematic of TTCS test loop at NIKHEF.

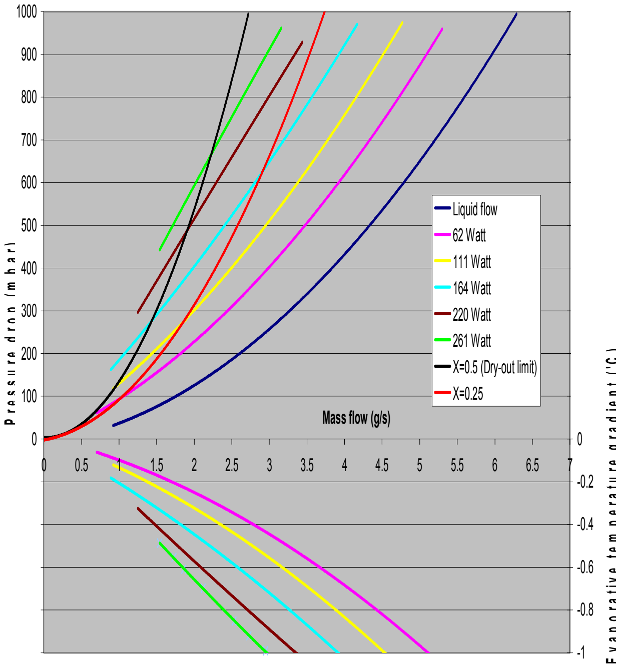


Figure. 13. Power dependence of pressure and temperature drops at 273 K.

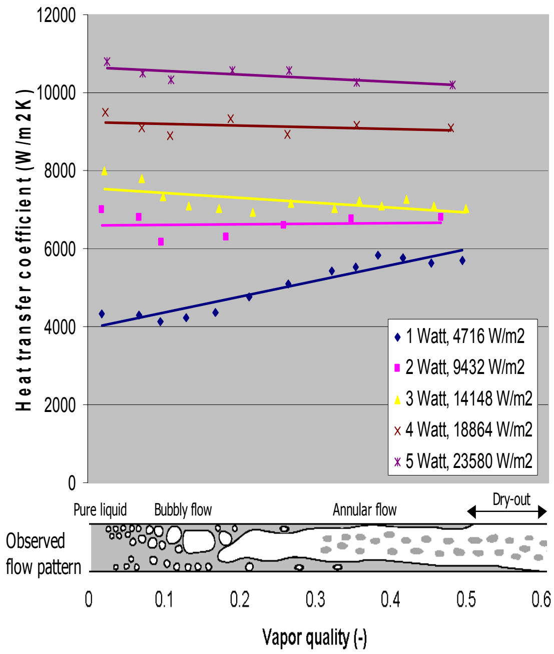


Figure 14. HTC and power (density) versus observed flow patterns and vapour quality at 2.7 g/s & 278 K.

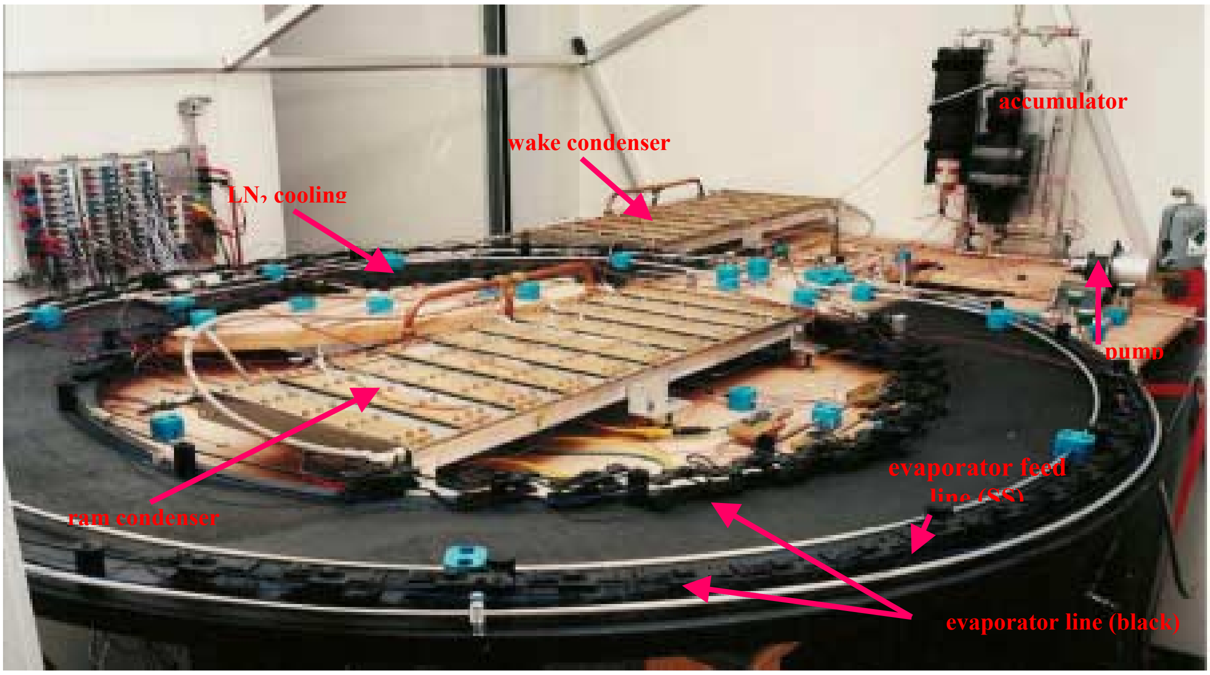


Figure 15. Picture of full-size simulation test rig at NLR.

Finally it is remarked that preliminary test results confirm the usefulness of the presence of a heat exchanger as pre-heater between the in- and outlet of the evaporator [12]. It was observed that up to say 90% of the heat collected in the evaporator could be reused for pre-heating the sub-cooled liquid coming from cold radiators. This amount of heat replaces part of the power to be added to te electric pre-heater that has to condition the liquid such that the fluid entering the evaporator is a pure liquid, at set-point saturation temperature as desired. It is obvious that the above yields a substantial power saving. Apart from this power saving impact, it can be said that the presence of the heat exchanger has also a stabilising effect on the temperature excursions of the evaporator during orbital radiator temperature variations.

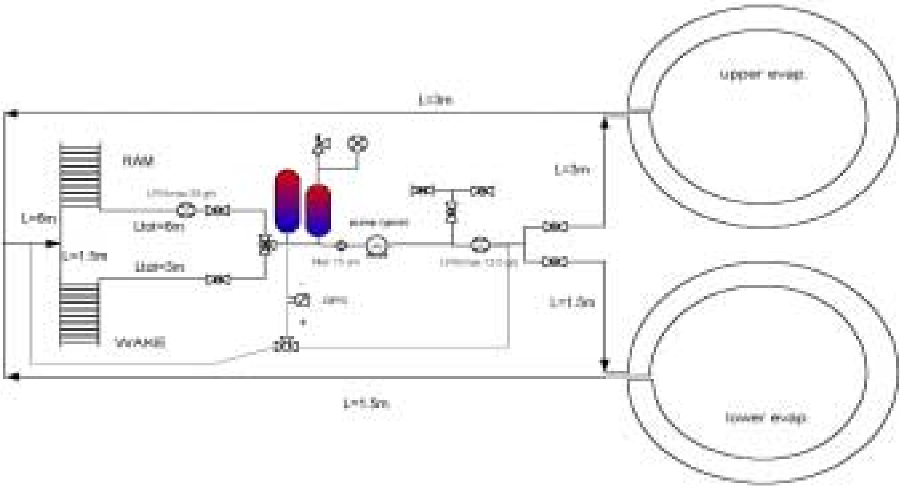


Figure 16. Schematic of NLR's full-size simulation test rig.

Figure 17. Evaporator.

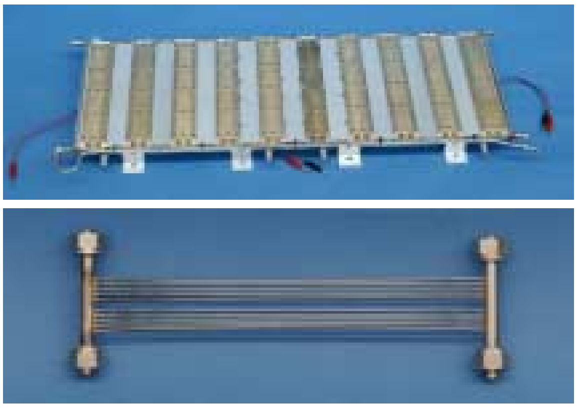


Figure 18. TTCS condenser & condenser element.

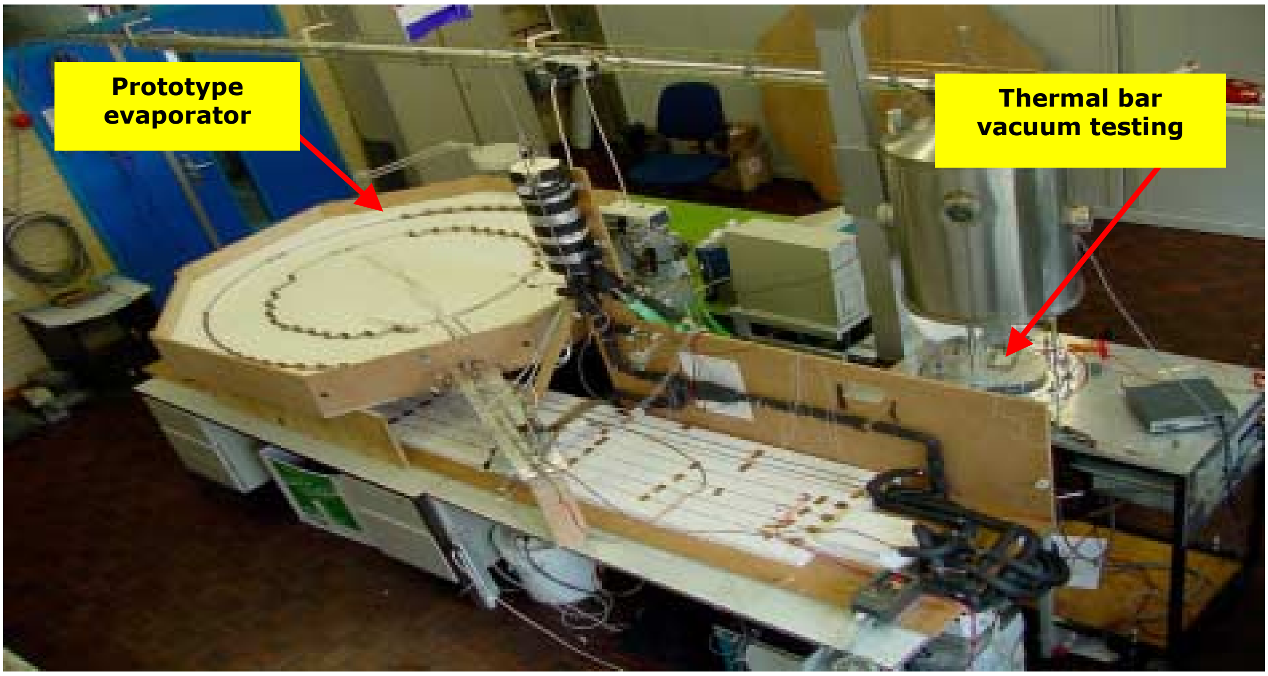


Figure 19. NIKHEF's evaporator & thermal bar (in vacuum) test loop.

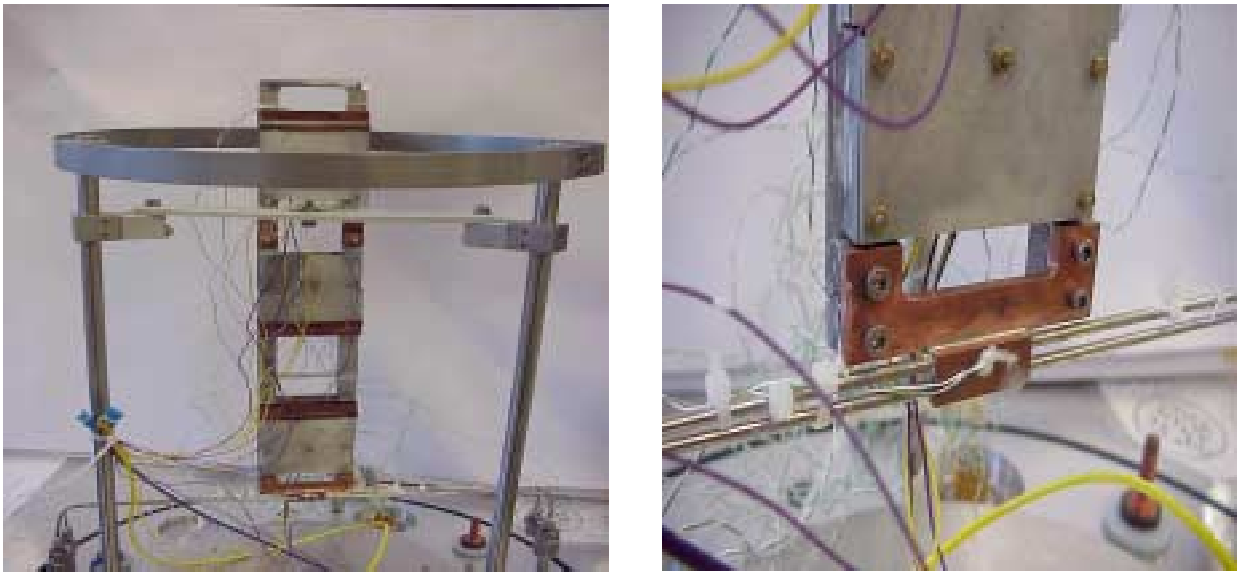


Figure 20. Thermal bar array with CO_2 evaporator connection for thermal vacuum testing and detail of connection.

The next step in the development was the creation of a full-scale test set-up at NLR for a more realistic simulation of the TTCS. A preliminary rig was designed and built. Based on experimental results obtained with this rig, the full-scale test set-up was designed and manufactured. Figure 15 shows a photograph of the current test set-up in the NLR climate chamber. Figure 16 depicts the schematic of the set-up. Details are shown in figure 17 (evaporator) and in figure 18, a specimen of the baseline TTCS condensers, consisting of 10 elements, which will interface the Ram & Wake heat pipe radiators (Fig. 5). The first experiments with this full-size test set-up yielded very encouraging results: The pressure drops across the system turned out to be even smaller than predicted: Almost ideal isothermality is approached.

To study the heat transfer in vacuum, along the thermal bar and from thermal bar to loop evaporator, a test rig was built at NIKHEF (Figs. 19, 20). Experiments are currently carried out. Some results will be presented in the next chapter.

THERMAL MODELLING

Calculations with a very detailed transient TTCS model (Fig. 21) have been done for many possible orbital (environmental loading) cases. The outcomes clearly indicate that [13]:

- The TTCS will operate without problems at the nominal loop set-point temperature 273 K, for the nominal case and most other thermal loading cases (Fig. 22).
- The set-point temperature of the loop has to be increased by up to say 10 K in some hot orbital cases (Fig. 23).
- The incorporation of the heat exchanger between evaporator in- and outlet considerably reduces the pre-heater power needed (Fig. 24).
- Figure 25 proves that the outcomes of the measured thermal bar temperature gradients and the thermal modelling predictions are in close agreement.

Currently the modelling is being refined and more accurate environmental loading conditions were recently provided by the “AMS Overall Thermal” main contractor. Using these new boundary conditions, new calculation runs were executed for various orbital environments and loop temperature set-points. The first results are shown in the figures 26 and 27.

IN-ORBIT EXPERIMENTS AND FINAL REMARKS

Apart from the challenge to develop a novel two-phase thermal control system for such an advanced experiment as AMS-2, NLR interest also pertains to the acquiring of in-orbit experience with real two-phase thermal control systems. NLR joined the AMS Collaboration, as it was guaranteed that the AMS-2 dormant (non-operation) periods could be used by NLR to execute dedicated experiments to study in-orbit two-phase heat transport system technology issues. Therefore the TTCS will be equipped with some extra heaters, sensors, and meters. The baseline philosophy will be that:

- There is minimum risk for Tracker and AMS-2.
- Any period AMS is not active can be used for thermal experiments
- There is at least one week of thermal experiments during the first six months
- Minimum power and mass will be added.
- The TTCS loop will, in principle, not be intruded.

Figure 28 depicts how complicated such a fully redundant, for extra NLR experimentation equipped, TTCS can look like. However, it can already be said now that AMS-2 overall mass reduction requirements certainly will lead to a less complicated system. This will realised by partly reducing the redundancy level required and by the deleting of some components.

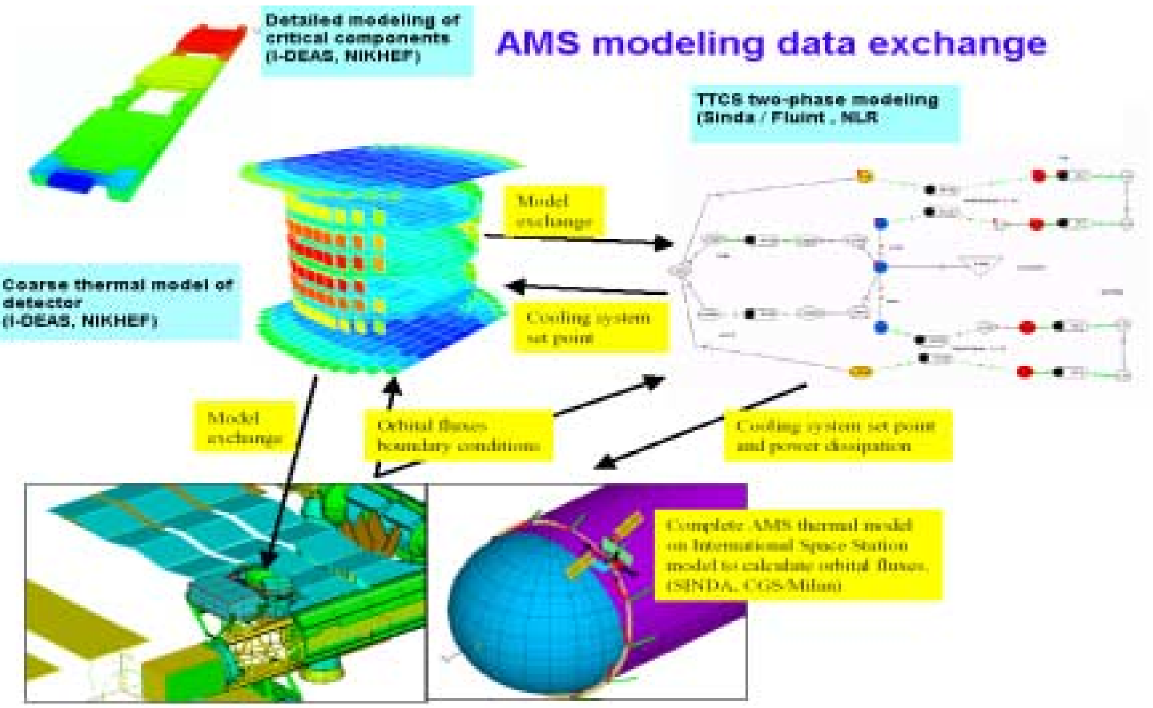


Figure 21. AMS-2 Modelling data exchange diagram.

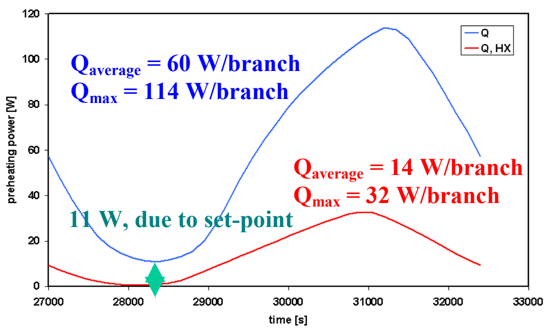


Figure 22. Influence of presence of heat exchanger.

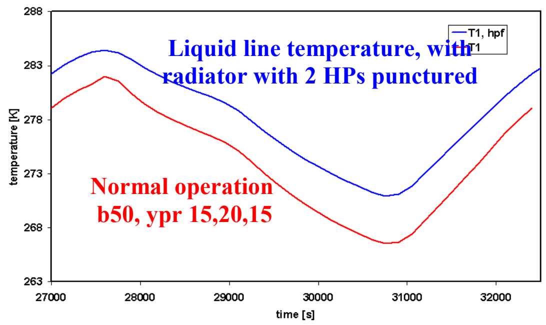


Figure 23. TTCS response to failure of 2 heat pipes.

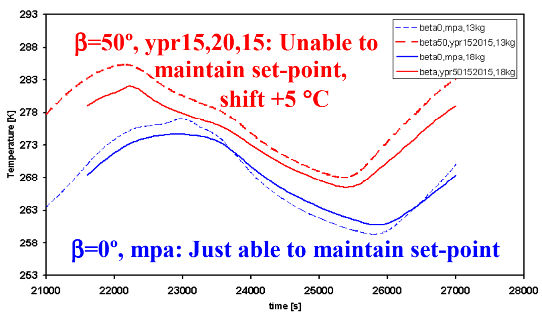


Figure 24. Liquid temperatures entering pump: Effect of total mass of radiators (2x13 kg/2x18 kg) & orbit.

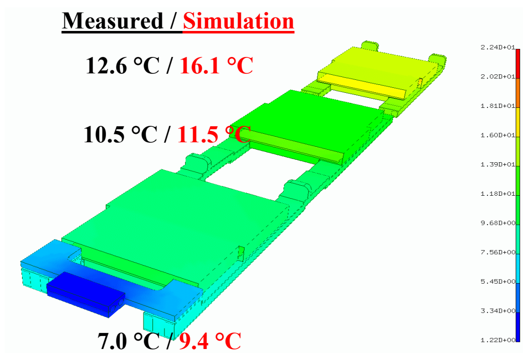


Figure 25. Thermal bar Modelling and simulation results.

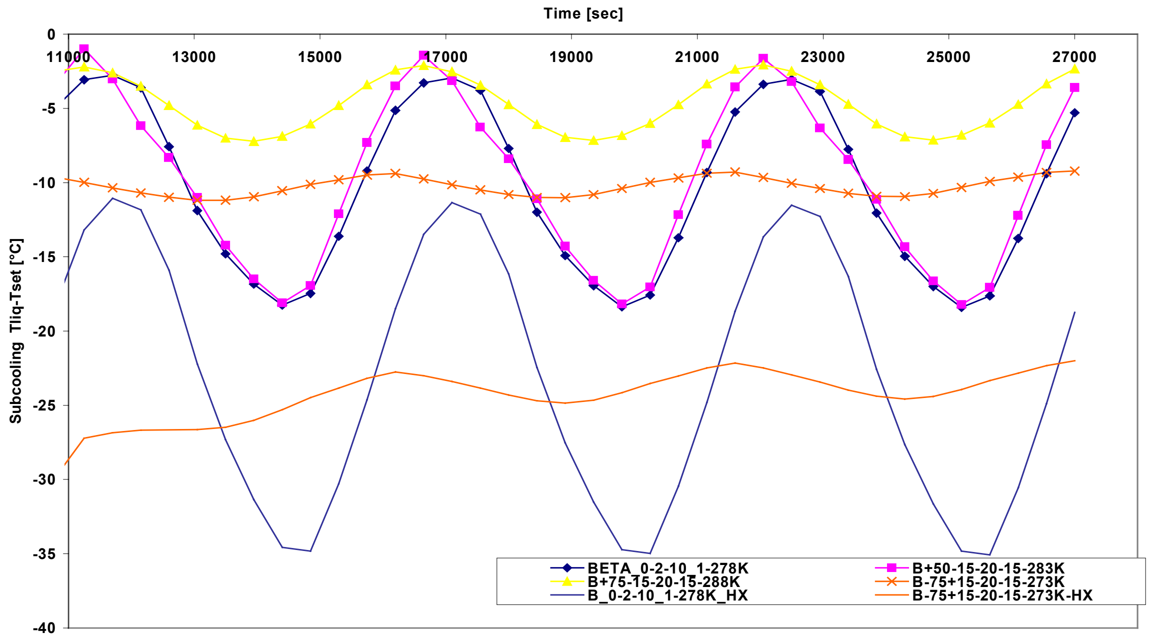


Figure 26. New liquid sub-cooling results for several orbits and set-point temperatures, with and without heat exchanger.

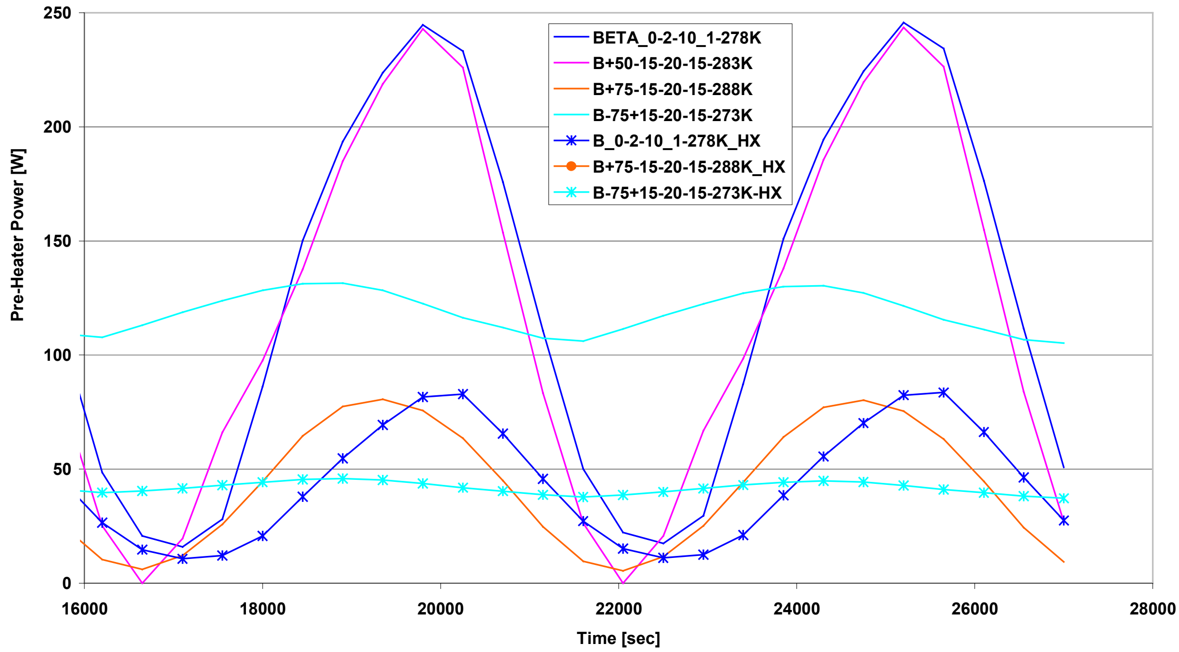


Figure 27. New results for several orbits and set-point temperatures, with and without heat exchanger.

As said before the mechanical pumps are critical issues in the TTCS, because of:
- The almost complete lack of in-orbit experience with mechanical pumps, certainly not for long duration missions as the AMS-2 mission.
- The working fluid CO_2, which has to operate at set-point temperatures, which can be relatively close to critical point.

As a consequence of the above, the baseline TTCS philosophy is to include two or even three pumps per loop. These currently developed pumps are upgraded versions of the Mars Rover pump, being adapted for CO_2-operation.

In conclusion it can be said that, though there is much work to be done, the Tracker Thermal Control System is on the proper track.

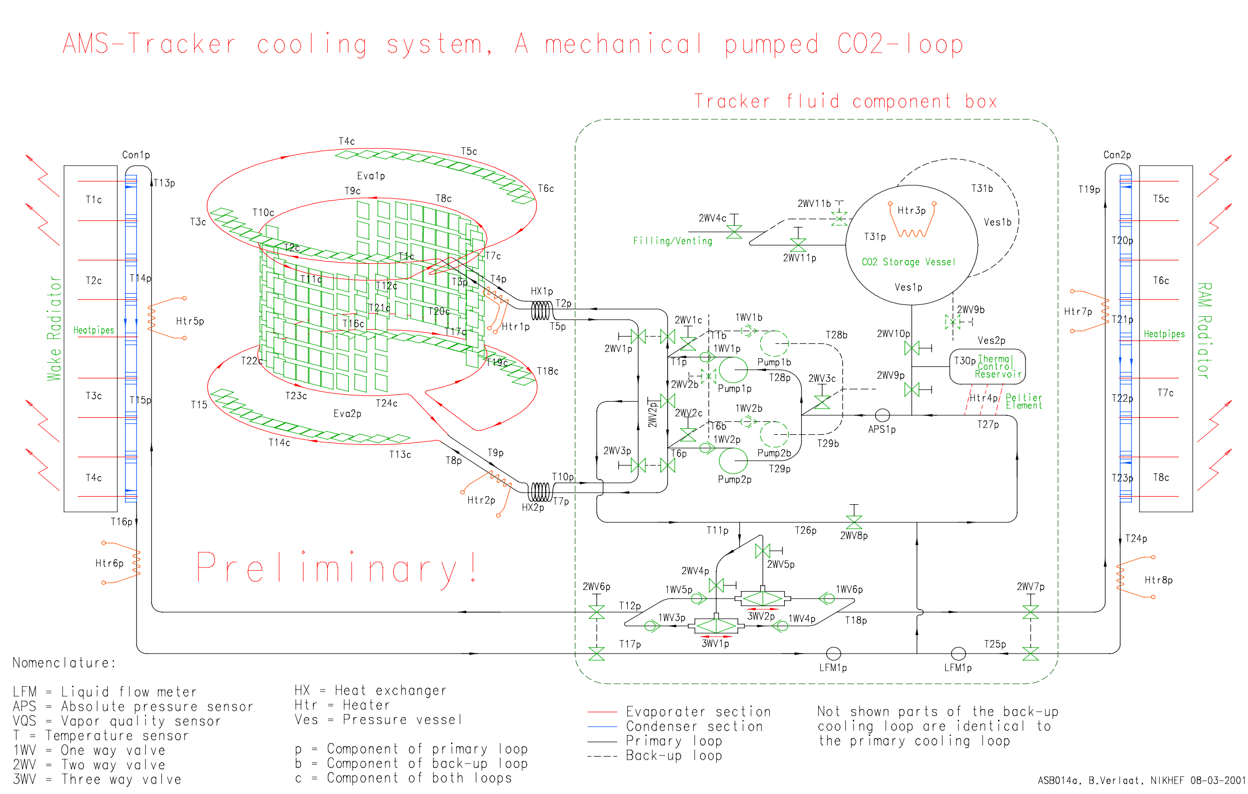


Figure 28. Preliminary fully redundant TTCS, equipped with extra experiment components.

NOMENCLATURE

AMS	Alpha Magnetic Spectrometer
APS	Absolute Pressure Sensor
CPL	Capillary Pumped Loop
DAC	Data Acquisition & Control System
DPS	Differential Pressure Sensor
DP	Pressure Difference (Pa or mBar)
HTC	Heat Transfer Coefficient ($W/m^2.K$)
INFN	Italian Institute for Nuclear Physics
ISS	International Space Station
LFM	Liquid Flow Meter
LHP	Loop Heat Pipe
MPL	Mechanically Pumped Loop
NIKHEF	Dutch Inst. for Nuclear & Particle Physics
NLR	Dutch National Aerospace Laboratory
RICH	Ring Imaging Cherenkov Counter
SPL	Single-Phase Loop
SINTEF	Norwegian Foundation for Scientific and Industrial Research
SRD	Synchrotron Radiation Detector
STS	Space Transportation System (Shuttle)
TC	Thermal control
TM	Thermal Model(ling)
ToF	Time of Flight
TPG	Thermal Pyrolytic Graphite
TPHTS	Two-Phase Heat Transport System
TRD	Transition Radiation Detector
TTCS	Tracker Thermal Control System
VQS	Vapour Quality (Mass Fraction) Sensor

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